

# **SIMULATION OF HEURISTIC LOT-SIZING AND SEQUENCING PROCEDURES IN MRP**

*A Thesis Submitted  
in Partial Fulfilment of the Requirements  
for the Degree of*

**MASTER OF TECHNOLOGY**

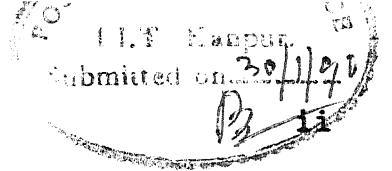
*by*

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*to the*

**INDUSTRIAL AND MANAGEMENT ENGINEERING PROGRAMME  
JAI PRAKASH SANDEEP UNIVERSITY OF TECHNOLOGY KANPUR**

**JANUARY, 1990**



## C E R T I F I C A T E

It is certified that the work contained in the thesis entitled " Simulation Of Heuristic Lot-Sizing And Sequencing procedures in MRP " by Vishnu Potty.S has been carried out under our supervision and that this work has not been submitted elsewhere for a degree.

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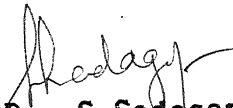
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## A B S T R A C T

Material requirements Planning is currently being used extensively in the industry. To attain a trade-off between setup costs and inventory carrying costs, it is necessary to lump the demand of more than one period into one lot. Hence a decision is to be taken regarding the appropriate lot sizing rule to be followed. There are also bound to constraints on the capacity which makes it imperative to take a decision regarding which scheduling rule to follow.

The present work details a simulation study which was carried out to determine the interaction effect between the various lot sizing & sequencing rules in MRP systems and aims to arrive at certain generalizations regarding their effect on the various performance criteria. The sensitivity of the different lot sizing rules and sequencing rules with regard to the various performance criteria was also studied. It is hoped that the results of this research would help the practitioner in taking a more pragmatic approach while choosing a combination of lot sizing and sequencing rule for the MRP system.

When lot sizing is carried out at different levels, and the capacity constraints are tight, the "Cascade effect" may become significant. This may lead to a situation where there is too much of inventory of some parts and too little of other parts. Two heuristic procedures, one which selectively reduces the lot sizes and another which selectively increases the production lead time of certain selected components were tried

out. These heuristics did give encouraging results on a couple of important criteria like Number of stockouts and units stockout, although they led to increased overall costs.

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Vishnu Potty

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## CHAPTER I

### INTRODUCTION

Materials Management is at the heart of all manufacturing concerns. Indeed, it accounts for a very important share, not only in the financial transactions of the enterprise, but also in the operational aspects of the enterprise. Seventy percent of the costs involved in producing a product is on materials. Hence the management of materials, more often referred to as Inventory Management is of paramount importance for the manufacturing enterprise.

Traditional Inventory Management approaches, in the precomputer days, could obviously not go beyond the limits imposed by the information processing tools available at the time. Because of this, almost all of these approaches and techniques suffered from imperfections. The commercial availability of computers in the mid-fifties ushered in a new era. The breakthrough in this area lies in the simple fact that once a computer becomes available, it becomes feasible to sort out or revise previously used techniques and to institute newer ones. In the area of Manufacturing Inventory Management, the most successful innovations are embodied in what has become known as Material Requirements Planning system, popularly referred to as MRP. Material Requirements Planning system has become a new way of life in production and inventory management, displacing older methods in general.

MRP is both an Inventory Control and a scheduling technique. It consists of a series of steps which starts by

determining what finished products are needed to meet the demand by time-periods, and arrives at a time schedule of the finished product components needed at each assembly for each time period.

Materials Requirements Planning systems were developed more than a decade ago to meet the need of the manufacturers for better inventory control in complex assembly processes. A distinctive feature of these processes, which renders traditional inventory control techniques inappropriate, is that the demands (and resulting schedules ) for all components from raw materials to subassemblies to finished assemblies are directly dependent on the schedule of requirements for higher level assemblies. This concept, termed dependent demand is exploited by MRP system to coordinate the inventory ordering policies for all the components of the manufacturing processes. Coordination is vital since shortage of a single item can halt the assembly process, resulting in sharply diminished productivity and increased inventory costs. The MRP approach is eminently suitable for the management of inventories subject to dependent demand, as it does not rely on any assumptions regarding the patterns of demand and inventory depletion.

MRP systems were made possible by the emergence of the computer as a fast economical information processor. Although the growth in the acceptance of these systems has paralleled that of the Computers, many of the Material Requirements Planning System in use today are, unfortunately, little more than data-processors.

As far as the role of MRP in a total manufacturing control system is concerned, it is seen that MRP is right in the middle of

total control system. The effectiveness of MRP is dependent on receiving good and accurate inputs. Two of these inputs are those concerning the Lot Sizing rule and Sequencing rule to be followed. It is important to realize that MRP by itself is not a panacea for a Manufacturing Control System, but it is a vital ingredient of a total control system.

### 1.1 Lot Sizing And Scheduling Decisions.

Manufacturing Lot-Size problem is one of converting the requirements into a series of replenishment orders. If we consider this problem on a local level, that is only in terms of one part and not its components, the problem involves determining how to group the requirements data into a schedule of replenishment orders that minimizes the sum of set up costs and inventory carrying costs. Thus Lot-sizing decisions which achieves economies of scale are important in MRP.

Since processing a lot through a workcentre takes time, it affects the other parts which are to use the same facility. ie, The flow time of other jobs in the queue are affected. This in turn affects the upper level items and ultimately the completion time of the end products. Again, in most situations there are limitations with regard to the available capacity. Hence a decision is also to be arrived at regarding which part is to be produced next, since it is not possible to produce all parts simultaneously.

Thus two of the important decisions to be taken in Material Requirements Planning are those concerning the appropriate Lot-Sizing and sequencing techniques to be

followed. The decision maker is definitely more interested in the likely performance that any combination of Lot-sizing and sequencing is likely to bring about. Some of these performance criteria are Number of late orders, Units of stockout, Number of setups, inventory carrying costs, etc... The choice of Lot-Sizing and Sequencing do affect the various performance criteria listed above and others.

### 1.2 Why Simulation.

The development of a mathematical model which takes into account the lot-sizing of parts at different levels of the product structure, and also the sequencing rules while scheduling the parts on each work-centre is quite complex. The size of even a small-size problem would be large. Moreover the collection of statistics to study the interaction between the lot-sizing & sequencing would be difficult if a mathematical model is used. Therefore a Simulation approach, defined as "the process of creating the essence of reality without ever actually attaining that reality itself" was adopted for this work.

### 1.3 Scope Of The Present Work.

It is indeed possible that a particular lot-sizing rule could work in an "opposite direction " to a particular sequencing rule, perhaps even nullifying all the desirable features of that lot-sizing & sequencing rule and, at the same time multiply the undesirable features of them. A computer simulation study was conducted to determine the effects of using the different lot-sizing rules and sequencing rules on the

various performance criteria in a multi-product, multi-stage production-inventory system using Material Requirements Planning. Hence the interaction effects could be quite significant to the practitioner. One of the primary aims of the research was to determine whether a particular lot-sizing rule and a sequencing rule are to be selected independently of each other or together.

One of the important points to be noted in using lot-sizing formulas is that they don't take into account the available capacity. Lot-sizing techniques frequently result in an order quantity so large that the periods in which those order quantities are taken up for production, they block up the movement of other parts which use the same facilities. When lot-sizing is applied to different levels the "cascade effect" may be magnified. The present work details two heuristic procedures which have been tried out in an attempt to arrive at a more feasible solution, when lot-sizing is carried out at different levels.

#### 1.4 Organization Of The Thesis.

Chapter two briefly describes the literature survey that was necessary before the work was begun.

Chapter three describes some of the fundamental concepts of MRP. explaining some important MRP terminologies, the methodology of MRP and when to use MRP.

Chapter four describes the present work, the Simulation study that was performed and the statistical analysis carried out on a set of eight sample problems. The detailed results of one problem and the summarized results of all the eight problems are given. The two heuristic procedures are explained in detail and

the results are also given at the end of the chapter.

Chapter five describes the conclusions arrived at and a short discussion on them and the scope for future works.

## CHAPTER II

### LITERATURE SURVEY

The effects of different lot sizing rules and sequencing rules on various performance criteria have been studied extensively. As noted by Biggs et.al [ 1 ] the use of P in a multi-stage, multi-product production inventory management system does not obviate the need for making the sequencing decisions regarding lot-sizing and sequencing.

There are numerous lot sizing rules that have been developed for use in traditional systems. Orlicky [ 2 ] lists nine such lot sizing procedures, but none of them have been developed for use in an MRP system. The individual effects of various Lot-Sizing methods on the performance of a multi-stage, multi-product production-inventory system using Material Requirements Planning have been reported by Biggs [1]. It was observed that though Wagner Whitin algorithm was the optimum solution methodology for the single level problem, it did not perform as well as the other lot sizing rules like Silver Meal Heuristic & Part-period Balancing procedures in the multi-stage production-inventory problem.

There are a large number of sequencing rules and exhaustive research on them have been reported by Conway et.al. [ 3 ] and Baker [ 4 ]. Vollman et.al [ 5 ] describes eleven such procedures, but all of them have been developed for use in the traditional job-shop environment.

A simulation study of priority rules in shop

floor situation under various levels of capacity is reported by Biggs [ 1]. The Shortest Processing Time Rule had performed well with respect to the number of stockouts and the setups. The Critical Ratio Rule which is based on the ratio of the effective lead time remaining to the work remaining had performed the best for the number of stockouts and also performed reasonably well for the other performance criteria.

Some lot-sizing heuristics which recognizes the multi stage requirement pattern have also been developed. Blackburn et.al.[ 6 ]. describes a procedure where coordination of lot sizing at different levels is achieved. But the binding conditions are that each part can have utmost one successor or parent, only pure assembly processes are to be considered and there should be no capacity constraints.

Very little research work has been reported on the use of multi-pass algorithms for capacity constrained situation. Moreover though the performance of different lot sizing and sequencing procedures have been reported, not much work has been reported where the interaction effects were studied.

## CHAPTER III

### AN OVERVIEW OF MRP

This chapter briefly describes the concepts of Material Requirements Planning (MRP), the methodology of MRP, (ie, how it works), and some of the decisions to be taken in MRP that greatly affect the system performance and about the factors that affect the computation of the requirements. However the objective of this chapter is to provide a general overview, rather than an in-depth coverage of the technical details.

MRP is widely used in business as, the mechanics of MRP are fairly simple in concept. It is a methodology for managing inventory and planning orders for parts and materials with dependent demand, that is demand which is derived from the demand of other item(s). An important point, but oft forgotten, is that MRP cannot stand by itself. It is only a component element of a total manufacturing control system. MRP needs the organizational support for its success. A manufacturing control system without MRP is severely limited in most of the situations.

#### 3.1 Assumptions And Prerequisites Of MRP

MRP systems imply several pre-requisites and reflect certain fundamental assumptions on which these systems are based. The first prerequisite is the existence of a Master Production Schedule, ie an authoritative statement of how many end items are to be produced and when to produce them.

Another requirement is that each item be unambiguously identified through an unique part number.

The existence at planning horizon of a Bill of Material is also a prerequisite. The Bill of Material must not merely list all the components of a given product, but must be structured so as to reflect the way the product is actually made, in steps from raw material to component part to sub-assembly to assembly to end item.

Another prerequisite to MRP is the availability of inventory records for all of the items under the system's control containing inventory status data.

An MRP system presupposes that the lead times for all inventory items are known and can be supplied to the system, at least as estimates. The lead times used for planning purposes normally must have a fixed value. This value can be changed at any time, but more than one value cannot be in simultaneous existence. An MRP system cannot handle indeterminate item lead times.

Another assumption under MRP is discrete disbursement and usage of component materials. For instance if fifty units of a component item is required for a given order, the MRP logic expects that exactly fifty units will be consumed. Materials that come in continuous form do not meet this expectation clearly and therefore require that standard planning procedures be modified.

In determining the timing of item gross requirements, the standard MRP procedure assumes that all the components of an assembly must be available at the time an order for that assembly is to be released to the factory. Thus the basic assumption is that the several components are

consumed for all practical purposes simultaneously.

It is clear that the application of MRP is generally limited to discrete manufacturing. In other words MRP is applicable to any discrete item, manufactured or purchased that is subject to dependent demand.

### 3.2 Methodology Of MRP

Materials Requirements Planning is a technique or really a set of systematic procedures for managing inventory in a manufacturing operation [ 7 ]. It is common to talk of "dependent versus independent demand". Demand is called independent when it is not related to the demand for any other item. Demand for finished products are examples of independent demand. Demand is called "dependent" when it derives from the demand for another item. The demand for component sub-assemblies, parts and raw materials is dependent.

Material Requirements Planning is concerned with dependent demand items. MRP generates time phased requirements for component parts which are effective forecasts of the future demand. There are four basic steps to the MRP process [ 7 ].

1. Netting.
2. Lot Sizing.
3. Offsetting.
4. Exploding.

### 3.2.1 Netting

Netting is subtracting of on-hand quantities from gross requirements to give the net requirements. Gross requirements is a statement of the anticipated future usage of or demand of the item. The gross requirements are time-phased, which mean that they are stated on a unique period by period basis, rather than aggregated or averaged. Table 3.1 shows the gross requirements by period for a typical component item. This item has a current balance of inventory on-hand of fifteen units and an open replenishment order of 120 units which is scheduled to be received in the first period. Therefore the net requirements in the first two periods are zero and are reduced related to gross-requirements in the third period. After the third period the gross requirements and the net requirements are the same.

Table 3.1

Time Period :	1	2	3	4	5	6
Gross requirements	50	75	90	100	35	100
Scheduled Receipts	120	0	0	0	0	0
Net Requirements	0	0	80	100	35	100

On-hand :15

### 3.2.2 Lot Sizing.

Lot Sizing is the determination of the individual batch or ordering quantities for manufacturing, based on the calculated time-phased net requirements. There are many alternative techniques available for lot-sizing which will be discussed later. Some of the techniques involve economic balancing of set-

up and inventory-carrying costs, and others are simpler rules such as using a fixed number of period requirements. To demonstrate the concept of lot sizing, the latter mentioned rule will be used. Lot quantities will be set equal to two period requirements. Table 3.2 shows the resulting planned lot quantities.

Table 3.2

Timeperiod :	1	2	3	4	5	6
Net requirements	0	0	80	100	35	100
Lot quantities			180		135	

### 3.2.3 Offsetting

Offsetting is the determination of the appropriate time for release of the planned orders so that they will be completed in time to satisfy the demand. The planned order release date is determined by subtracting the lead time from the date of earliest net requirement which it is intended to satisfy. In the example which has been shown in tables 3.1 & 3.2, if the lead time is two periods then the planned order releases are as follows.

Table 3.3

#### Example of offsetting

Timeperiod :	1	2	3	4	5	6
Gross Requirements	50	75	90	100	35	100
Planned receipts	120		180		135	
Planned orders	180		135			
On-hand quantity :	15					

### 3.2.4 Explosion

Explosion is the process of translating the product requirements into component part requirements, taking existing inventories and scheduled receipts into account. Thus explosion may be viewed as the process of determining for any part number, the quantities of all components required to satisfy its requirements, and continuing this process for every part number until all purchased items and/or raw material requirements are exactly calculated.

### 3.3 Lot Sizing in MRP.

Several formal procedures have been developed for lot sizing the time phased requirements. The basic trade-off usually involves the elimination of one or more setups at the expense of carrying inventory longer. In many cases the discrete lot sizes that are possible with MRP are more appealing than the fixed lot sizes that could be used.

The lot-for-lot techniques seems to be at first glance to be too simple-minded, since it does not consider any of the economic trade-offs. Recall however that batching planned orders at one level will increase the gross requirements at the next level in the product structure. So larger lot-sizing near the end-item level of the Bill Of Materials cascades down through all the levels. Thus it seems that the lot-for-lot sizing approach is better than one might expect in actual practice, particularly when it is applied at the top and the intermediate levels of the product structure. This is especially the case when the product structure is too deep.

the cascade effect is greatly magnified. As a consequence Lot for lot approach is used at the top levels and lot-sizing techniques are employed only at the lower levels of the product structure.

Orlicky [ 2 ] lists nine Lot-sizing procedures. The three Lot-sizing methods that have been used in the simulation analysis are explained briefly here.

1. Part Period Balancing.
2. Silver Meal Heuristic.
3. Wagner Whitin Algorithm.

### 3.3.1 Part Period Balancing.

The part period balancing procedure uses all of the information provided by the requirements schedule. In determining the lot size for an order this procedure tries to equate the total costs of placing the orders and carrying inventory [ 5 ]. It can be illustrated through an example.

Example problem:

Week No	:	1	2	3	4	5	6	7	8	9
Requirements:		10	10	15	20	70	180	250	270	280

Ordering Costs : Rs 100 per order.

Inv carrying costs : Rs 2 per unit per week.

The alternative lot sizes available at the beginning of the week 1 are to place an order covering the requirements for

1. Week 1 only.
2. Weeks 1 & 2.

3. Weeks 1,2 & 3 .

4. Weeks 1,2,3 & 4.

5. Weeks 1,2,3,4 & 5 etc.

The inventory carrying costs are based on the average inventory for the period . Hence the  $1/2$  (average for one period),  $3/2$  (average for two weeks) etc. The inventory costs for the above options are

$$1. \text{ Rs } 2 \left( (1/2) \cdot 10 \right) = \text{Rs } 10.$$

$$2. \text{ Rs } 2 \left( (1/2) \cdot 10 + (3/2) \cdot 10 \right) = \text{Rs } 40.$$

$$3. \text{ Rs } 2 \left( (1/2) \cdot 10 + (3/2) \cdot 10 + (5/2) \cdot 15 \right) = \text{Rs } 115.$$

$$4. \text{ Rs } 2 \left( (1/2) \cdot 10 + (3/2) \cdot 10 + (5/2) \cdot 15 + (7/2) \cdot 20 \right) = \text{Rs } 255.$$

Similarly the costs for the fifth option is Rs 885.

In this case the inventory carrying costs for alternative 4 most nearly approximates the setup costs of Rs 300. Therefore an order should be placed at the beginning of the first week and the next ordering decision need not be made until the beginning of the week 5. The procedure is then repeated. This procedure permits both the lot size and the time between orders to vary. Thus, it will result in smaller lot sizes and longer time intervals between orders in the periods of low requirements than those occurring for periods of high requirements.

### 3.3.2 Silver Meal Heuristic.

The silver meal Heuristic procedure selects the replenishment quantity so that the total relevant costs per unit time-period for the duration of the replenishment

quantity is minimized [ 8 ]. The idea is to use an approach use an approach which captures the essence of the time varying complexity, but at the same time remains relatively simple for the practitioner to understand and does not require lengthy computations. If a replenishment arrives at the beginning of the first period and it covers the requirements through to the end of the  $T^{\text{th}}$  period, then the criterion function [ 9 ] can be written as follows,

$\text{TRCUT}(T) := (\text{Setup Cost} + \text{Total carrying costs to end of period } T) / T;$   
 where TRCUT stands for Total Relevant Costs per Unit Time.

The basic idea of the heuristic is to evaluate  $\text{TRCUT}(T)$  for increasing values of  $T$  until for the first time  $\text{TRCUT}(T+1) > \text{TRCUT}(T)$ . Then the lot size is equal to the demand for these  $T$  periods. For the problem described in section 3.3.1, the values of  $\text{TRCUT}(T)$  for  $T$  ranging from 1 to 5 are

$$\text{TRCUT}(1) := (300 + (1/2) \cdot 10) / 1 = \text{Rs } 305.$$

$$\text{TRCUT}(2) := (300 + (1/2) \cdot 10 + (3/2) \cdot 10) / 2 = \text{Rs } 160.$$

$$\text{TRCUT}(3) := (300 + (1/2) \cdot 10 + (3/2) \cdot 10 + (5/2) \cdot 15) / 2 = \text{Rs } 115.$$

Similarly the values for  $T$  equal to 4 & 5 are respectively Rs 99 and Rs 118.

Since  $\text{TRCUT}(5) > \text{TRCUT}(4)$ , the decision in the first period is to order for that quantity sufficient to cover the demands for the first four weeks. The next reordering decision need not be taken until the start of the fifth period. The method described above guarantees only a local minimum in the total relevant costs per unit time. It is however possible that still larger values of  $T$  will yield still lower costs per unit time.

### 3.3.3 Wagner Whitin Algorithm.

Wagner Whitin algorithm is designed to find optimal ordering policies for problems with known demand and varying setup and inventory carrying costs over an N-period planning horizon [ 9 ]. The computation proceeds as follows

Let

$D_t$  = Demand through period 1 to T.

$I_t$  = Inventory carrying costs in period t.

$S_t$  = Set up costs in period t.

$Q_t$  = quantity ordered in timeperiod t.

$F_k$  = Optimal policy costs for the periods 1..T.

$M_{jk}$  = Setup and carrying costs during the periods j+1 to k when  
the lot size satisfies the demand for periods j+1 to k.

Then

$F_k = \text{Min } F_j + M_{jk}.$

With reference to the problem described in section 3.3.1, the values of  $F_j$ 's are given in the table.

Last Production Period	Time Period --->					
	1	2	3	4	5	6
1	120	160	250	410	1110	3870
2		240	300	420	880	2680
3			290	370	790	2130
4				390	670	1650
5					610	1330
6						1070

The values of  $Q_t$ 's are 20, 35 70 and 180 respectively in the periods 1,3,5 and 6.

There are two theorems which reduce the computations required. The first theorem basically suggests considering programs where  $I_t^*Q_t=0$ , is nothing is ordered for any period when inventory is brought into that period.

According to the planning horizon theorem, if it is optimal to incur an ordering cost in period  $t^*$  then it is sufficient to explicitly consider periods 1 through  $t^*-1$  separately. Thus the planning horizon theorem allows the decomposition of the original problem into smaller problems leading to a further reduction in the amount of computations.

### 3.4 SEQUENCING IN MRP.

In addition to the decision as to what the lot size should be for each and every item, another important decision to be taken is that concerning when to produce these lots. There are a large number of sequencing rules which have been developed and tested, but mostly in the traditional job-shop environment.

Sequencing rules can be classified as static or dynamic [ 5 ]. A static rule is one for which the necessary input information is available at the beginning of the simulation itself. A dynamic rule is one for which the priority values have to be recomputed time and again. Four sequencing

rules which have been used in the present simulation study are explained in brief below.

### 1. S.P.T

Process that component lot first that has got the shortest processing time. It has been reported that S.P.T rule performs well with respect to number of setups and inventory costs [ 6 ].

### 2. Critical Ratio Rule.

Process that component lot first that is most needed in the next period(s). The critical ratio [7] is calculated using the formula,

Critical Ratio= Lead time remaining - Work remaining

Work Remaining

The job lot having the least critical ratio is given the highest priority. This rule has performed well with respect to the stockouts, as reported by Biggs[ 1 ].

### 3. Unit Value Rule.

Process that component lot first that has the highest unit value.

### 4. End Product Value Rule.

Process that component lot first that is a component of the final product with the highest unit cost. This rule was selected because it was thought that it would increase the value of the end-product flow through the system.

### 3.5 Factors Affecting The Computation Of Requirements.

#### 3.5.1 Common Usage Of Components.

Common usage of a component item by several parent items is another complicating factor in the computation of requirements by an MRP system. Lower the level of the component item, the more parent items it tends to have. In order to determine the net requirements for such common usage items correctly, its gross requirements stemming from all of its parent items must be determined first. For this purpose, Low level coding is applied.

#### 3.5.2 Low Level Coding

The technique of low-level-coding is commonly employed. The lowest level at which any inventory item appears is identified through an analysis of the Bill Of Material file and this information is added to the Bill of Materials record. In the level by level requirements computation process, processing of the item is delayed until the lowest level on which it appears is reached. At that point all the possible requirements of that item stemming from all of its parent items have been established.

#### 3.5.3 Lead Times.

Planned production lead times are used by an MRP system. The lead time of a part is made up of different components like queue times, running time, setup time, inspection time,

move time etc. Orlicky [ 2 ] reports that in a machine shop environment, the first of the elements listed normally accounts for roughly ninety percent of the total elapsed time.

Lead times are to be stated in terms of the planning period being used. When, as is the usual case, the planning period equals a week or longer, many minor distractions may occur. When lead time is one day, the system interprets it as one week. Sometimes the distortion due to this could be extreme as when a part A is made one day, the next day it is consumed in making sub-assembly B which in turn goes into assembly C built on third day. In cases like these to prevent the MRP system from planning these items one week apart their lead times may be specified as zero. The system will then order for all three in the same week.

### 3.6 Where To Use MRP.

MRP is a way of life for many industries fabricating and assembling products like automobiles and radios. It is especially suitable for situations where one or all of the following conditions exist.

1. Final product is complex, and made up of several levels of assemblies.
2. Lead times for components and raw materials are relatively long.
3. Manufacturing cycle is long.
4. Consolidation of requirements for several products is desirable so that economic lot sizes are applicable.

MRP is a dynamic system which is continually changing,

if changes are too frequent and involve short lead times, then the system will not be able to overcome the inertia in the system. Manufacturing will also have trouble in making changes in capacity, which is critical, for one cannot get more out of the system than what capacity permits.

## CHAPTER IV

### SIMULATION STUDY

A simulation model of a multi-product, multistage production-inventory system was developed. Simulation does provide the advantages of a method of analyzing the problems that cannot be solved by other techniques. However the solution arrived at by Simulation are only as broadly applicable as the simulation model is similar to its real world counterparts.

The individual effects of Lot-sizing and Sequencing have been studied separately. This Simulation study was conducted to examine the interaction effects of different lot-sizing and Sequencing rules when used conjunctively. In other words the study aims to determine the interaction effects between lot sizing and sequencing in order to arrive at a decision as to whether a lot sizing and a sequencing rule are to be selected independently or in conjunction.

The Material Requirements Planning system converts the Master Production Schedule into a time-phased schedule for all the intermediate assemblies and component parts. The quantities and timings for planned orders are determined by the Material requirements Planning logic using the Inventory position, gross requirements and a specific procedure for determining the quantities ,the lot sizing procedure.

#### 4.1 Lot Sizing Rules Considered.

A number of procedures have been developed for MRP systems, ranging from ordering ( Lot-for-Lot ) to simple decision rules and finally to extensive optimizing procedures. The lot sizing procedures used in this simulation analysis are

1. Part Period Balancing.
2. Silver Meal Heuristic.
3. Wagner Whitin Algorithm.

All of the above lot sizing procedures are explained in brief in Chapter 3. All of them will tend to combine the net requirements for more than one time-period/bucket. No fraction of a time periods requirements will be split into two or more different lots by any of the above mentioned lot-sizing rules.

#### 4.2 Sequencing Rules Considered

The mechanics of MRP simply generate a set of net requirements that must be met if the Master Production Schedule is to be maintained. After selecting the Lot Sizing rule, the decision maker is still left with the decision of when to produce these appropriate lot sizes. Hence the need for scheduling or sequencing arises.

However, most of the Sequencing rules have been developed in the traditional job shop environment where a lot/batch maintains a unique identification from the beginning of the process to its being shipped to the customer. There has been very little research into the use of a set of sequencing

rules in a discrete manufacturing process which has inventory at each stage.

The sequencing rules which have been used in this simulation study are the following.

1. Critical Ratio Rule.
2. End product Value Rule.
3. Shortest Processing Time.
4. Unit Value Rule.

All of the above four sequencing rules have been explained in brief in the preceding chapter.

#### 4.3 Simulation Model

There is the necessity for the conceptualization of the following general hypothesis. In a multi-stage, multi-product, production-inventory system using Material Requirements Planning, the choice of lot-sizing and sequencing rule will have noticeable effects on the performance criteria, and these two sets of rules will interact. A production-inventory system with different inventory levels- raw materials, parts, assemblies and finished goods is conceptualized. The model uses discrete time-periods of one week for updating and taking decisions.

##### 4.3.1 Assumptions

To evaluate the effects of lot-sizing and sequencing and of the interaction effects between the two, it is necessary to incorporate many simplifying assumptions as far as the system is concerned. These assumptions relate to

the product demand, product lead times, informational capabilities and possible interactions between them . These basic assumptions are the following.

1. Demand is deterministic.
2. Breakdown times and repair times of the machines are deterministic.
3. Manpower is of uniform capability.
4. Pre-empting is not allowed.
5. Machine set-up time and operation times are known.

The issue of capacity utilization while a matter of great importance to the practitioner ,was not part of this work. For the purposes of this study it was considered more appropriate to take into account capacity constrained situations. Accordingly the demand of the end products have been taken to be at a level which made a severe demand on the capacity. The capacity utilization of the work centers ranged from seventy percent to as high as ninety percent.

It is also assumed that no work center can perform more than one operation at any time. Each lot size, once started must be completed if the component parts are available. That is, machine or work-center availability, while being a constraint on the total production will not limit a production lot, but can cause part of that lot to be shifted to the following time period.

#### 4.3.2 Performance criteria

Four performance criteria have been used to evaluate

the various combination of sequencing rules and lot-sizing rules. They are the following;

1. Number of Stockouts.
2. Units Stockout.
3. Inventory Cost.
4. Number Of Setups.

Very frequently it is seen that the performance of a manufacturing concern is judged on the basis of number of late orders, or in other words the punctuality of delivering the parts as ordered. Therefore this performance criteria was considered to be important and was selected.

The second criteria, the number of units of stockout indicate the extent to which the consumer demands have been successfully met. This criteria also has a bearing on the profitability, and more importantly on the goodwill of the consumer, which is of paramount importance.

The third criterion, inventory carrying costs indicates the extent to which capital has been locked up and has a direct influence on the profits earned.

The fourth criterion, the number of setups is also important, especially when the changeover times from one setup to another setup are significant.

To statistically analyze the interaction between lot sizing and sequencing, it is necessary to have more than one simulation run for the same combination of lot sizing and sequencing rules. Unless the number of replications is greater than one, it will not be possible to test for interaction effects. Each combination of lot-sizing and sequencing rule is tested five times with the demand of the final products changed between replications. To change the demand of the end products between replications, a random number generating routine is used. The time horizon considered was fifty time-periods/'buckets'. The time-period considered was a week. The statistics were collected only after a preliminary run for five periods.

The simulation was repeated for eight sample problems. For three of the sample problems considered, the product structures were predominantly broad, for three other problems the structure was predominantly deep and for the remaining two problems it was a combination of the above two.

For illustrative purposes, the details of one problem are given here. The number of end products considered were four and the total number of parts were forty five. The product structures of the four end products are given in Figures 4.3.3.1 to 4.3.3.4.

The demand of the four end products have been assumed to be uniformly distributed for this problem. The values are given in the table 4.3.3.1. The subassembly details are given in the

table 4.3.3.2. The work center where the assembly process takes place and the time taken to assemble per unit are given in the table.

The routing details of the parts are given in the table 4.3.3.3. The numbers within the brackets indicate the work center where the process takes place and the time taken to process per unit. The machining sequence of a part is the same as given in the table.

#### 4.3.4 Statistical Testing.

The statistical analysis was performed using the two way Analysis of Variance approach. The analysis of variance is a widely used technique for separating the variance in a group of samples into portions which are traceable to different sources [10 ]. The details of this procedure is given in Appendix A. If all the samples are lumped together into one grand sample, it would not be possible to determine the individual effects of various factors. The method of analysis of variance enables one to estimate how much of the variance is attributable to one cause and how much to the other cause, and to decide whether or not the interaction between the two factors have produced any significant effects. Thus it is possible to estimate the effects of lot-sizing and sequencing simultaneously.

The detailed results of the problem described in section 4.3.3 are given in the tables 4.3.4.1 to 4.3.4.11.

Tables 4.3.4.1 to 4.3.4.4 are the summarized statistics

Figure No. 4.3.3.1 Product Structure No.1

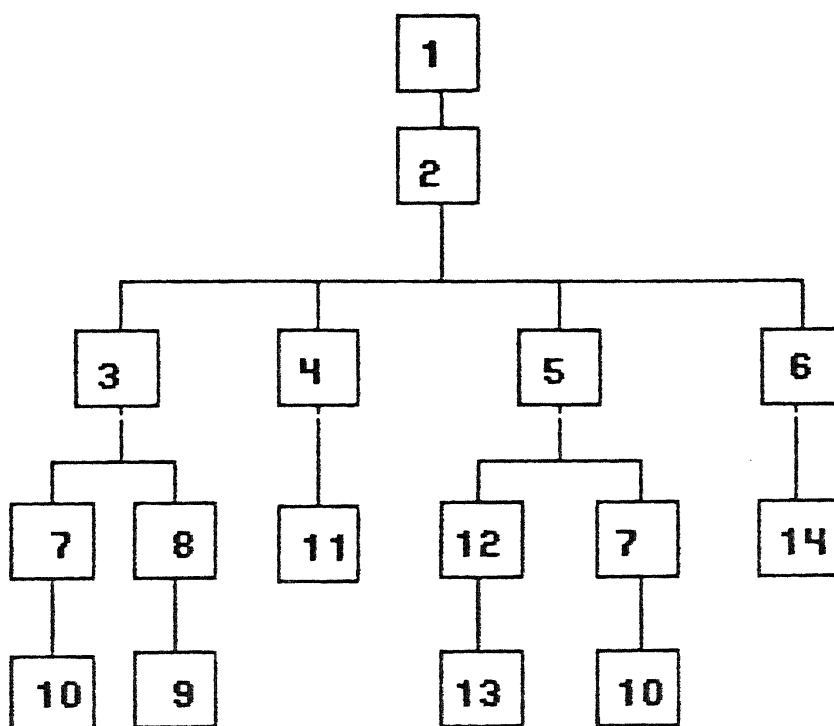


Figure No. 4.3.3.2 Product Structure No.2

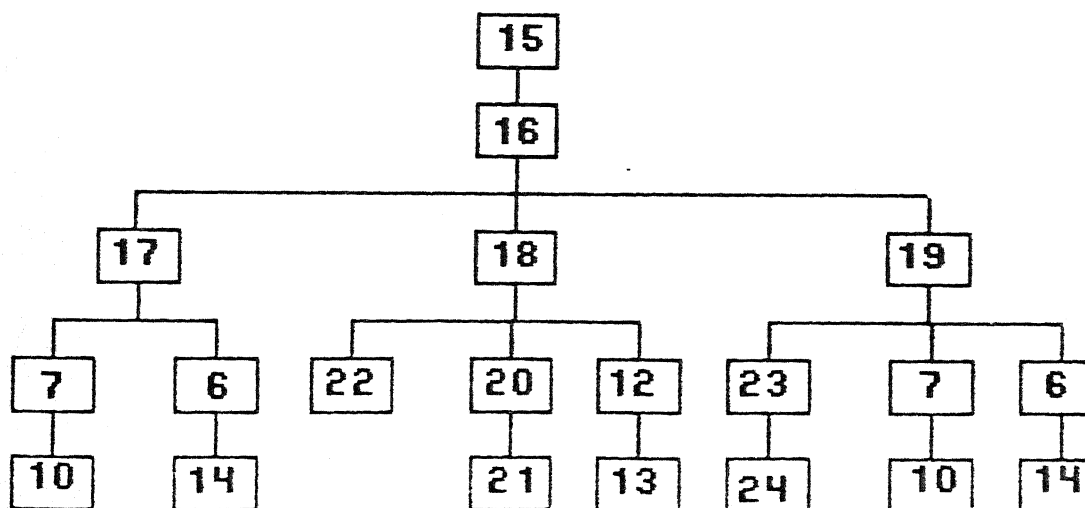


Figure No. 4.3.3.3 Product Structure No. 3

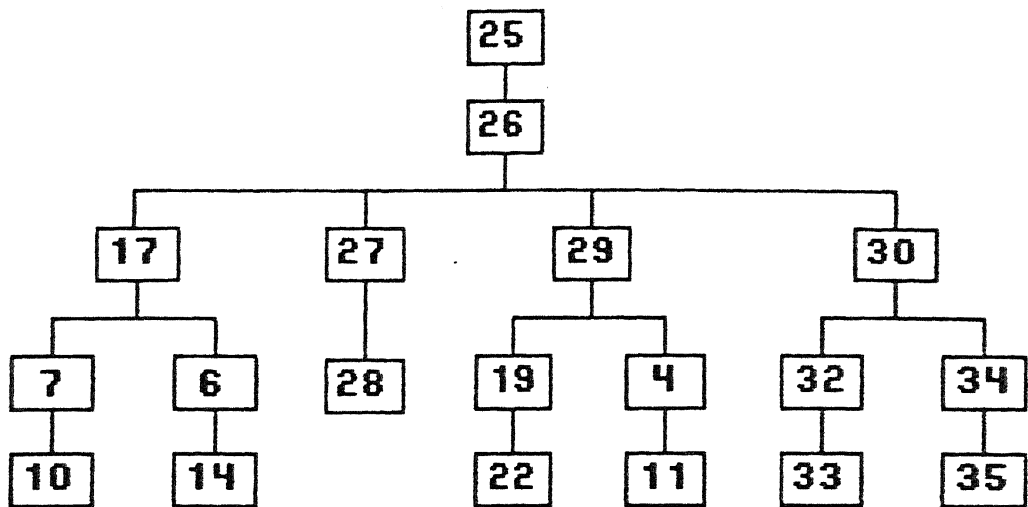


Figure No. 4.3.3.4 Product Structure No. 4

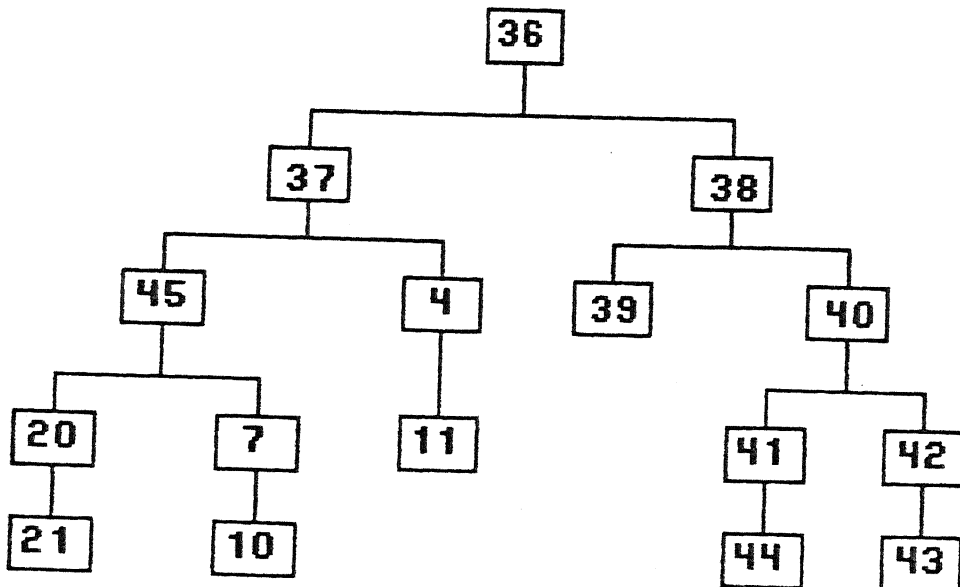


Table 4.3.3.1

## Demand Data Of Product

Product No	Demand/timeperiod
1	$U^*(40,60)$
15	$U(25,40)$
25	$U(30,40)$
36	$U(40,50)$

Table 4.3.3.2

## Sub Assembly details

Part No	Work Center	Time per assembly
2	1	40
3	2	45
5	3	30
16	4	25
17	3	15
18	1	20
19	2	30
26	3	34
29	4	20
30	5	45
36	4	15
37	5	20
38	4	20
40	5	25
45	1	30

\* Uniformly distributed

Table 4.3.3.3  
Routing Details Of Parts.

Part No	Routing Sequence.		
2	( 6 , 10 )	( 7 , 15 )	( 8 , 10 )
10	( 9 , 8 )	( 8 , 15 )	
9	( 7 , 20 )	( 8 , 10 )	
11	( 9 , 10 )	( 10 , 10 )	( 12 , 12 )
13	( 10 , 7 )	( 12 , 10 )	
14	( 9 , 5 )	( 10 , 4 )	( 11 , 8 )
16	( 10 , 2 )	( 11 , 5 )	( 12 , 5 )
21	( 6 , 15 )	( 11 , 2 )	
22	( 6 , 25 )	( 11 , 20 )	
24	( 6 , 10 )	( 8 , 3 )	( 12 , 5 )
28	( 8 , 5 )	( 10 , 5 )	( 12 , 5 )
31	( 9 , 10 )	( 10 , 10 )	( 11 , 5 )
26	( 8 , 3 )	( 10 , 3 )	( 6 , 10 )
33	( 9 , 4 )	( 8 , 5 )	( 7 , 10 )
35	( 7 , 10 )	( 9 , 6 )	( 10 , 8 )
43	( 9 , 4 )	( 10 , 6 )	( 12 , 8 )
44	( 8 , 5 )	( 10 , 7 )	

The number's in the brackets indicate the work centre and the time taken to process per unit.

r the individual performance measures. The numbers in each cell are the mean and standard deviation for a particular combination of lot sizing and a sequencing rule. They represent twenty replications. The marginal values for the columns are the means and standard deviations for a particular lot sizing rule over all the sequencing rules and represent twenty replications. The marginal values for the rows are the grand means for a particular lot sizing rule over all the sequencing rules and represent fifteen replications each. The ANOVA ( Analysis Of Variance ) tables are given in the tables 4.3.4.5 to 4.3.4.8.

### 4.3.5 Interpretation Of Results.

The significance level of Lot Sizing, Sequencing and their interaction effects are given in the tables 4.3.4.9 to 4.3.4.11. It is important to note that the interaction effect between lot sizing and Sequencing are significant, though at varying levels for the different performance criteria.

Lot sizing was found to be less significant than sequencing in the case of the two performance criteria, namely number of stockouts & units stockout. It can be stated that the above two criteria are more sensitive to changes in sequencing procedures than to changes in lot sizing procedures.

In the case of setups, it is found that lot sizing is more significant than sequencing. In other words, it can be said that number of setups are more sensitive to changes in lot sizing procedures than to changes in sequencing procedures.

The discussions so far have centered around the row means and column means. But it is significant to note that the interaction effects are significant. For example though the combination of Part-Period Rule and Critical Ratio Rule gives the best solution in case of the number of stockouts & number of units of stockout, the combination of Part-Period balancing & Unit Value rule performs very badly against the same two criteria. Again the combination of Part Period balancing & Unit Value rule gives the best solution for the number of setups. But the same combination gives bad results for the other two criteria.

Since there are four performance criteria and they do not all show equal response to various rule combinations, there is indeed a difficulty in interpreting them for practical usage. To the practitioner it only means that he should be very careful in choosing a combination of lot sizing & sequencing rules. It is hoped that the user friendly system developed will be of help to the decision maker in arriving at a solution that will be acceptable to him. If the criteria of the practitioner is single-valued then he can refer to the corresponding table and choose that combination which will result in a minimization of that criteria. However if the decision maker is looking for minimizing multiple criteria, it is to be remembered that he should not have a myopic point of view. The tables obtained as output from the simulator could be referred to and that solution chosen which would perform satisfactory for all the criteria. This is because a combination which performs the best for a criteria may perform very badly for the other criteria.

It could be said that there is no universal combination of lot sizing & sequencing rule that would perform the best for multi-criteria situation.

### 3.6 Summary Of Results

The simulation was carried out for eight problems. Though clear-cut conclusion on what lot sizing rule and sequencing rule is to be chosen for a multi-criteria situation could not be arrived at, the statistical analysis does provide us with some information of the sensitivity of the lot sizing rules and sequencing rules to different performance criteria. This is bound to be of help to the practitioner while he wishes to maximize the performance of his system. A summary result of the simulation carried out on the eight problems are given in the tables 4.3.6.1 to 4.3.6.3, which indicate the range of the significance values of lot-sizing & sequencing rules and of their interaction, for the set of eight sample problems considered. It is hoped that the practitioner would stand to benefit from this.

Some of the observations from an analysis of the eight problems are the following.

1. In all the problems, Sequencing rules were found to be more significant than Lot sizing rules for the performance criteria of Number of stockouts and Units Stockout.
2. In all the problems, Lot sizing was found to be more significant than sequencing in the case of Number of setups.
3. The interaction effects were found to be quite significant

for all the performance criteria with the significance values ranging from 0.50 to 0.01.

#### 4.4 Heuristic Procedures Developed.

Under conditions of tight capacity, it may be impossible to prevent any stockouts. However it is seen that sometimes the lot sizes of certain parts are such that the periods in which they are taken for production, they block up the other parts which are to be processed in those machines.

Here two heuristic procedures, one which attempts to reduce the lot sizes of the parts through an iterative procedure, and the second which increases the lead times of certain parts through an iterative procedure are presented.

##### 4.4.1 Heuristic 1.

Let

$T$  = Length of the planning horizon.

SOPWDC = Set of parts with difference in actual & theoretical costs exceeding 10 %.

SOPC = Set of parts already considered twice in the iterative procedure.

BestSol = Best Solution arrived at w.r.t Stockouts.

$K(j)$  = Number of times the part  $j$  has been considered in the iterative procedure.

The iterative procedure for modifying the lot sizes is as follows-

1. Initialize all  $K(j)$  to be 0 where  $j$  represents the part

number.

2. Read Input Data.
3. Simulate for the time horizon considered.
4. BestSol  $\rightarrow$  solution arrived at in step 3.
5. Form the set SOPWDC.
6. Remove all parts  $j$  from the set SOPWDC where  $K(j) = 2$ .
7. If No of stockouts equals zero or if SOPWDC equals null or SOPWDC is a subset of SOPC then stop.
8. Select the part from the set SOPWDC whose holding cost is highest. Let the part be denoted by  $P_j$ .
9. If the lot size of the part  $P_j$  cannot be changed THEN the part  $P_j$  is removed from the set SOPWDC and go to step 5 ELSE Increase the holding cost of the part  $P_j$  in steps of 0.2 until the lot size of the part changes. Simulate and store the present solution. If the present solution is better than the BestSol then BestSol  $\rightarrow$  present solution. Increment  $K(P_j)$ . Add part  $P_j$  to the set SOPC if  $K(j) = 2$ . Go to step 5.

The results of the iterative procedure carried out on the sample problem are given in the table 4.4.1. It is seen that the number of stockouts have reduced, though at a slight increase in the overall costs.

#### 4.4.2 Heuristic 2.

In this heuristic an iterative procedure is followed which increases the lead times of the selected parts in steps of one period. The procedure is as follows- (with the same notations as followed in Heuristic 1)

number.

2. Read Input Data.
3. Simulate for the time horizon considered.
4. BestSol  $\rightarrow$  solution arrived at in step 3.
5. Form the set SOPWDC.
6. Remove all parts  $j$  from the set SOPWDC where  $K(j) = 2$ .
7. If No of stockouts equals zero or if SOPWDC equals null or SOPWDC is a subset of SOPC then stop.
8. Select the part from the set SOPWDC whose holding cost is highest. Let the part be denoted by  $P_j$ .
9. Change the lead time of the part by one unit, increment  $K(j)$  by one. Simulate and store the present solution. If the present solution is better than the BestSol then BestSol  $\rightarrow$  present solution. Add part  $P_j$  to the set SOPC if  $K(P_j) = 2$ . Go to step 5.

The results of the simulation carried out are given in the table 4.4.2. The solution arrived at is more feasible in the sense that the number of stockouts are less. However the increase in the costs are quite significant.

A comparison of the results of the above two iterative procedures do indicate that in cases of tight capacity, it may be better to change the lot sizes than to change the lead times.

Table 4.3.4.1

Performance Criteria : Number Of Stockouts.\*

Lot Sizing Rules	Sequencing Rules					Row Means
	S.P.T	Critical Ratio Rule	End Product Value Rule	Unit Value Rule		
Wagner Whitin Algorithm	28.80 4.66	22.00 3.69	56.40 4.22	46.60 8.48		38.45
Part Period Balancing	24.40 5.57	20.60 4.76	58.80 3.71	53.60 3.88		39.35
Silver Meal Heuristic	28.20 2.64	21.00 6.36	51.20 3.54	40.80 4.07		35.30
Column Means	27.13	21.2	55.47	47.00		

\* The values in the cell are the mean and standard deviation for the five replications.

Table 4.3.4.2

Performance Criteria : Units Stockout.\*

Lot Sizing Rules	Sequencing Rules				
	S.P.T	Critical Ratio Rule	End Product Value Rule	Unit Value Rule	Row Means
Wagner Whitin Algorithm	716.8 114.84	554.00 97.05	1318.80 101.75	1084.00 192.18	918.40
Part Period Balancing	612.80 134.75	462.6 118.39	1373 70	1168.20 91.79	904.15
Silver Meal Heuristic	730.20 58.83	514.80 156.22	1255 114.89	978.20 70.68	869.55
Column Means	686.60	510.47	1315.60	1076.80	

\* The values in the cell are the mean and standard deviation for the five replications.

Table 4.3.4.3

Performance Criteria : Number Of Setups.\*

Lot Sizing Rules	Sequencing Rules				
	S.P.T	Critical Ratio Rule	End Product Value Rule	Unit Value Rule	Row Means
Wagner Whitin Algorithm	3212.00 18.41	3188.60 19.50	3090.60 421.58	3114.40 23.11	3151.40
Part Period Balancing	3149.4 19.53	3122.80 30.42	2998.40 45.45	2982.20 30.79	3063.20
Silver Meal Heuristic	3246.2 16.49	3225.80 28.80	3120.40 24.62	3175.00 32.78	3191.85
Column Means	3202.5	3179.0	3069.8	3090.53	

\* The values in the cell are the mean and standard deviation for the five replications.

Table 4.3.4.4

Performance Criteria : Inventory Costs(in Rs).\*

Lot Sizing Rules	Sequencing Rules				
	S.P.T	Critical Ratio Rule	End Product Value Rule	Unit Value Rule	Row Means
Wagner Whitin Algorithm	301869.2 1441.98	305735.00 3087.79	306371.40 3462.39	306347.80 1847.51	305080.85
Part Period Balancing	308713.00 2111.48	312995.60 3535.78	316366.00 4302.95	316061.20 4614.52	313533.95
Silver Meal Heuristic	301514.40 2619.95	301173.20 3180.15	303930.40 1168.98	303542.20 599.82	313533.95
Column Means	304032.20	306634.60	308889.27	308650.40	

\* The values in the cell are the mean and standard deviation for the five replications.

Table 4.3.4.5

Anova Table :Number Of Stockouts

Variation Due To	Sum Of Squares	Degrees Of Freedom	Mean Squares	F value	Significance Level
Lot Sizing Effects	121	2	60	2.0	0.25
Sequencing Effects	11791	3	3930	132.9	0.01
Interaction Effects	443	6	74	2.5	0.05
Replication Effects	1420	48	30	-	-

Table 4.3.4.6

Anova Table :Units Stockout

Variation Due To	Sum Of Squares	Degrees Of Freedom	Mean Squares	F value	Significance Level
Lot Sizing Effects	25244	2	12622	0.74	0.50
Sequencing Effects	6018445	3	2006148	118.41	0.01
Interaction Effects	162605	6	27101	1.60	0.25
Replication Effects	813261	48	16943	-	-

Table 4.3.4.7

Anova Table: Number Of Setups

Variation Due To	Sum Of Squares	Degrees Of Freedom	Mean Squares	F value	Significance Level
Lot Sizing Effects	173108	2	86554	156.66	0.01
Sequencing Effects	190950	3	63650	115.20	0.25
Interaction Effects	15850	6	2642	4.78	0.01
Replication Effects	26520	48	553	-	-

Table 4.3.4.8

Anova Table :Inventory Cost

Variation Due To	Sum Of Squares( 10 <sup>5</sup> )	Degrees Of Freedom )	Mean Squares	F value	Significance Level
Lot Sizing Effects	13251.760	2	6625.88	62.00	0.01
Sequencing Effects	2283.576	3	761.93	7.13	0.01
Interaction Effects	606.912	6	101.15	0.95	0.50
Replication Effects	5124.418	48	106.75	-	-

Table 4.3.4.9

## Analysis Of Variance

Source Of Variation : Main Effects of Lot Sizing

Performance Criteria	F Statistic	Significance Value <sup>*</sup>
No of stockouts	2.06	0.25
Units stockout	0.745	0.50
Setups	156.657	0.01
Inv Cost	62.064	0.01

\* Degrees Of Freedom are 2,48

Table 4.3.4.10

## Analysis Of Variance

Source Of Variation : Main Effects of Sequencing.

Performance Criteria	F Statistic	Significance Value <sup>**</sup>
No of stockouts	132.853	0.01
Units stockout	118.406	0.01
Setups	3.657	0.05
Inv Cost	7.13	0.01

\*\* Degrees Of Freedom are 3,48

Table 4.3.4.11

## Analysis Of Variance

Source Of Variation : Interaction Effect Of Lot sizing & Sequencing.

Performance Criteria	F Statistic	Significance Value <sup>*</sup>
No of stockouts	2.49	0.05
Units stockout	1.60	0.25
Setups	4.781	0.01
Inv Cost	0.947	0.50

\* Degrees of Freedom are 6,48

Table 4.3.6.1

Range of Significance Values Of Lot-Sizing  
Rules For The eight sample problems.

Performance Criteria	Range Of Significance Values
No of stockouts	0.25 to -
Units stockout	0.25 to -
Setups	0.01 to 0.05
Inv Cost	0.01 to 0.05

Table 4.3.6.2

Range of Significance Values Of SequencingRules For The eight sample problems.

Performance Criteria	Range Of Significance Values
No of stockouts	0.01 to 0.05
Units stockout	0.01 to 0.05
Setups	0.25 to 0.50
Inv Cost	0.01 to 0.25

Table 4.3.6.3

Range of Significance Values Of InteractionFor The eight sample problems.

Performance Criteria	Range Of Significance Values
No of stockouts	0.01 to 0.25
Units stockout	0.01 to 0.25
Setups	0.25 to 0.50
Inv Cost	0.01 to 0.25

Table 4.4.1

Results of the Simulation carried out with  
Modification In the Lot Sizes.

Performance Criteria	Original Value	Modified Value	Percent change
Setups	3129	3234	3.36
No Of Stockouts	29	20	-31.03
Units Stockout	684	482	-29.53
Setup Cost (Rs)	417861	431594	-36.17
Inventory Cost(Rs)	317566	307561	3.29
Total Cost (Rs)	735427	739155	-3.15

Table 4.4.2

Results of the Simulation carried out with  
Modification In the Lead Times

Performance Criteria	Original Value	Modified Value	Percent change
Setups	3129	3143	0.45
No Of Stockouts	29	23	-20.69
Units Stockout	684	553	-19.15
Setup Cost( Rs )	417861	421673	0.91
Inventory Cost(Rs	317566	334104	5.21
Total Cost ( Rs)	735427	755776	2.77

## CHAPTER V

### CONCLUSIONS

One of the primary aims of the research was to determine whether a lot-sizing rule and a sequencing rule are to be selected independently or together. The statistical analysis carried out on the eight sample problems do tend to indicate that the sensitivity of lot-sizing and sequencing rules are different for the same performance criteria. It is also seen that the interaction effects are quite significant for some performance criteria. However no single rule was found to perform "the best" against all the four performance criteria considered. In selecting a particular lot-sizing and sequencing rule, a trade-off between the different performance criteria are required. There is no single combination which would do the best for all criteria.

The two heuristic procedure which attempted to coordinate the lot-sizing decision at different levels have produced encouraging results.

#### Scope Of Future Work.

An area of future work is to determine the pattern of difference in the significance levels of lot-sizing, sequencing & their interaction as a function of available capacity. A more rigorous study is required to arrive at more concrete conclusions, since the sample size considered was small.

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## Appendix A

### Analysis Of Variance.

The procedure used to test the equality of the means of several populations is called Analysis Of Variance. It involves splitting up of the variance into its component parts (analyzing it), and then deciding whether to accept or reject the equality of the population means based on the relative magnitude of these pieces. Analysis of variance enables one to estimate how much of the variance is due to one factor and how much is due to the other.

We will suppose that there are two factors, called as A-factor & B-factor respectively. We will suppose that A-effects occur at "a" levels, denoted by  $i = 1..a$ , and that the B-effects occur at "b" levels denoted by  $j=1..b$ . A variate X is measured on each item and it is replicated r times. In addition Let

$r$  = Number of replications within each cell.

$X_{ijk}$  = Value of the variate X measured with the  $i^{th}$  A-factor and  $j^{th}$  B-Factor for the  $r^{th}$  replication.

$X_{i..}$  = Grand row means for the  $i^{th}$  A-Factor.

$X_{.j.}$  = Grand column means for the  $j^{th}$  B-Factor.

$X_{ij.}$  = Mean of all replications within a cell.

$N$  = Total number of individual measurements of the variate X equal to  $abr$ .

Table A.1

Table Of Observations For ANOVA

A factor	B Factor ->			Row Means
	X <sub>111</sub> .			X <sub>1..</sub>
	X <sub>11r</sub>			
-----	-----	-----	-----	-----
i		X <sub>ij1</sub> X <sub>ij2</sub> .		X <sub>i..</sub>
		X <sub>ijr</sub>		
-----	-----	-----	-----	-----
Column Means	X <sub>.1.</sub>	X <sub>.j.</sub>		

We suppose that the  $i^{\text{th}}$  A-factor has an effect on the variate  $X$  measured by  $\alpha_i$ , the  $j^{\text{th}}$  B-factor has an effect measured by  $\beta_j$  and the interaction effect is denoted by  $\gamma_{ij}$ . The mathematical model can be represented by

$$X_{ijk} = \mu + \alpha_i + \beta_j + \gamma_{ij} + \epsilon_{ijk}$$

where  $\epsilon_{ijk}$  is the random part of  $X_{ijk}$  which is due to all the miscellaneous causes which may produce an effect, but which are not specifically allowed for in the design of the experiment and  $\mu$  is the overall arithmetic mean of the variate.

The total sum of the squares of deviation can be divided into its component parts as follows.

$$SST = SSA + SSB + SSAB + SSR$$

where SSA, SSB, SSAB & SSR are the sum of the squares of deviation due to A factors, B factors, the interaction and replication

$$SSA = b \cdot r \sum_i (X_{i..} - \bar{X})^2$$

$$SSB = a \cdot r \sum_j (X_{.j.} - \bar{X})^2$$

$$SSAB = r \sum_{ij} (X_{ij.} - X_{i..} - X_{.j.} - \bar{X})^2$$

$$SSR = \sum_{ijk} (X_{ijk} - X_{ij.})^2$$

The analysis of variance for the model can be set out as in the table.

Source of variation	Degrees Of Freedom	Mean Squares	F Value
A effects	a-1	$MS_a = SSA/(a-1)$	$MS_a / MS_e$
B effects	b-1	$MS_b = SSB/(b-1)$	$MS_b / MS_e$
A B effects	(a-1)(b-1)	$MS_{ab} = SSA^B/((a-1).(b-1))$	$MS_{ab} / MS_e$
Replication Effect	a.b.(r-1)	$MS_e = SSR/(a.b.(r-1))$	

The four sum of the squares are pairwise independent. It is possible to test for interaction by comparing the mean squares of interaction and replication and test for B-effects by comparing the mean squares of B-effects and replication, and test for A-effects by comparing the mean squares of A-effects and replication.

Once the F values are got, the significance values can be read from the table corresponding to the appropriate degrees of freedom.

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